

OBSERVATIONS OF SEDIMENT-LADEN ICEBERGS IN ANTARCTIC WATERS: IMPLICATIONS TO GLACIAL EROSION AND TRANSPORT

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ABSTRACT. Sediment-laden icebergs are rarely sighted in Antarctic waters. However, during the recent Deep Freeze 79-USCGC *Glacier* expedition to the George V Coast and the south-western Ross Sea, nine sediment-laden icebergs and several pieces of pack ice with surficial sediment layers were observed. These observations include basal debris zones, debris slumped on to glaciers and floating ice, and englacial debris believed to have been incorporated along shear zones.

Sediment samples collected from icebergs were texturally and mineralogically variable. Some were unsorted mixtures consisting of a wide variety of angular minerals and rock fragments; others consisted primarily of slate clasts, quartz sand, and rock flour.

RÉSUMÉ. *Observation d'icebergs chargés de sédiments dans les eaux de l'Antarctique: implications concernant l'érosion glaciaire et le transport des sédiments.* Des icebergs chargés de sédiments sont rarement signalés dans les eaux Antarctiques. Cependant, au cours de la récente expédition Deep Freeze 79-USCGC *Glacier* vers George V Coast et le Sud-Ouest de la mer de Ross, on a observé neuf icebergs chargés de sédiments et un nombre de morceaux de glace du pack avec des niveaux superficiels de sédiments. Ces observations comprennent des plages de matériaux issus du fond, des matériaux d'effondrement sur les glaciers et les glaces flottantes, et des matériaux intra-glaciaires que l'on pense avoir été prélevés le long des zones de cisaillement.

Les échantillons de sédiments recueillis à partir des icebergs étaient de texture et de composition minéralogique variables. Quelques uns étaient des mélanges non triés comprenant une large variété de minéraux angulaires et de fragments de roche; d'autres consistaient principalement en éclats schisteux, en sable quartzique et en farine de roche.

ZUSAMMENFASSUNG. *Beobachtungen sedimentbeladener Eisberge in antarktischen Gewässern: Folgerungen auf glaziale Erosion und Verfrachtung.* Sedimentbeladene Eisberge sind in antarktischen Gewässern selten zu sehen. Doch wurden während der jüngsten Deep Freeze 79-USCGC *Glacier*-Expedition an die George V Coast und in die südwestliche Ross-See neun sedimentbeladene Eisberge und einige Packeisstücke mit oberflächlichen Sedimentschichten beobachtet. Dabei zeigten sich Schutzzonen vom Untergrund, auf Gletscher- und Schelfeis abgestürzter Schutt und Innenmoränen, die vermutlich längs Scherzonen aufgenommen wurden.

Sedimentproben von Eisbergen waren in Textur und Mineralgehalt verschieden. Einige waren unsortierte Mischungen aus einer grossen Vielfalt von kantigen Mineralien und Felsstücken; andere bestanden vornehmlich aus Schieferbruchstücken, Quarzsand und Felsmehl.

INTRODUCTION

One of the most striking differences between Antarctic and Arctic glaciers has to do with the amount of debris they are observed to carry. Arctic glaciers and icebergs are typically laden with debris at all levels in the ice (Ovenshine, 1970), whereas Antarctic glaciers and icebergs have been reported to be, for the most part, barren of debris (Odell, 1952; Warnke, 1970). The apparent absence of debris in Antarctic icebergs is somewhat puzzling in view of the fact that surficial continental margin deposits commonly contain substantial quantities of ice-rafted sediment (Anderson and others, 1979). The question then arises as to whether the present is a period of diminished ice-rafting, or if the quantity of debris carried by Antarctic icebergs has been underestimated.

Questions concerning ice-rafting are important because variations in the quantity of ice-rafted debris (IRD) within the marine sedimentary record have provided one of the primary bases for paleoclimatic studies in Antarctica. Most models for ice-rafting assume that an increase in the IRD component of deep-sea sediments implies an advancing ice front. Most of the IRD deposited on the Antarctic abyssal floor is believed to be transported as englacial debris, because basal debris is probably deposited relatively close to the ice-shelf grounding line (Carey and Ahmad, 1961). Proper interpretation of IRD data is thus dependent upon understanding the mechanics of englacial transport.

The only known mechanisms for the englacial incorporation of originally subglacial debris involve thrusting (Goldthwait, 1951), basal freezing (Weertman, 1961; Boulton, 1970), and intrusion into basal crevasses (Hoppe, 1952; Mickelson, 1971). The third mechanism probably is not important in Antarctica at present because basal intrusion is thought to occur under conditions of mass wastage (Boulton, 1970). Both of the other mechanisms have been inferred for upper Ferrar Glacier of Victoria Land, Antarctica (Souchez, 1967). Other mechanisms by which debris is deposited on the surface of glaciers and floating ice include wind transport, avalanching, and ablation (Bellair and others, 1964). These processes have also been observed in Antarctica (Nichols, 1961). They are probably not important in terms of the total debris rafted out to sea in Antarctica today because exposed rock and sediment is so scarce.

METHODS

Eight samples of debris-laden ice were obtained. These were analysed for the weight per cent as well as the textural character of the incorporated sediment. Weights of the dirty ice were obtained on board ship and later, after melting and drying, weights of only the debris were used to calculate the weight percentages. Textural analyses were carried out using the partially automated sedimentology laboratory facilities at Rice University (Anderson and Kurtz, 1979).

ICEBERG OBSERVATIONS

There have been a number of published accounts of sightings of debris-laden icebergs in Antarctica. These are summarized in Table I; the locations of these sightings are shown in Figure 1. Unfortunately, these accounts generally do not contain enough descriptive information to determine how the sediment was incorporated.

Since 1970, the authors have participated in a number of Antarctic oceanographic expeditions (Fig. 1) and have made hundreds of iceberg observations. Prior to 1978, field work was concentrated in the Weddell Sea region and only two observations of icebergs which possibly contained sediment were made. More recently, during Deep Freeze 79, a more systematic iceberg survey was conducted along a series of closely spaced transects off the George V Coast (Fig. 1). Frequent helicopter flights were made to facilitate our observations. We observed, of a total of 370 icebergs, four of which contained debris (sightings 1 through 4; Fig. 2). Previously, during the Australasian Expedition of 1911-14, a number of debris-laden

TABLE I. SUMMARY OF PUBLISHED SEDIMENT-LADEN ICEBERG OBSERVATIONS. REFER TO FIGURE 1 FOR LOCATIONS

<i>Sighting No.</i>	<i>Reference</i>	<i>Position</i>	<i>Description</i>
8	Warnke and Richter, 1970	lat. 64° 46' S. long. 64° 06' W.	Bergy bit
9	Voronov and Kruchinin, 1961	Near Lazarev Ice Shelf	Sediment in shear zones
10	Kulikov, 1962	lat. 65° 20' S. long. 82° 02' E.	Overturnd iceberg, basal debris zone (25-40 m ²)
11	Yevteyev, 1960	Near Jones Glacier	Overturnd iceberg
12	Bellair and others, 1964	lat. 66° 37' S. long. 139° 52' E.	Overturnd iceberg, internal moraine
13	Oliver and others, 1978	McMurdo Sound	Horizontal layers
14	Nichols, 1961	McMurdo Sound area	Aeolian surface debris
15	Mawson, 1942	lat. 65° 18' S. long. 151° 50' E.	Debris embedded in large icebergs
16	Mawson, 1942	lat. 64° 35' S. long. 117° 01' E.	Overturnd iceberg

icebergs were also sighted in this region (Mawson, 1942). Most of the icebergs were probably derived from Mertz and Ninnis Glaciers which together comprise the major drainage system for this region.

En route to McMurdo Station, several additional sightings were made (sightings 5 through 7, Fig. 2). A summary of debris-laden iceberg observations from Deep Freeze 79 is given in Table II.

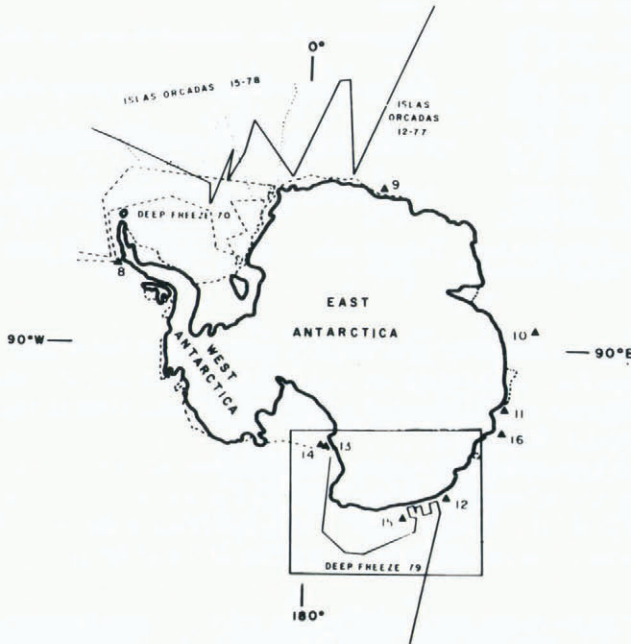


Fig. 1. Locations of reported sightings of sediment-laden icebergs in Antarctic waters. Tables I and II list data for each sighting. Cruise tracks of expeditions on which the authors have conducted iceberg observations are also shown.

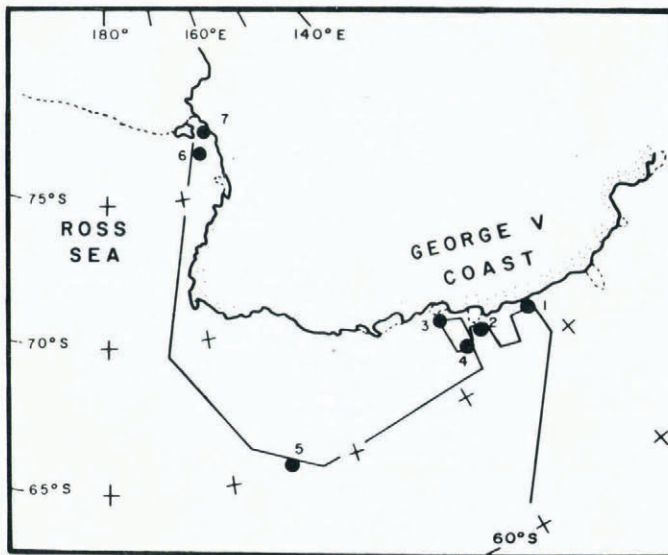


Fig. 2. The cruise track for the Deep Freeze 79-USCGC Glacier expedition and the locations of sediment-laden iceberg sightings.

TABLE II. SUMMARY OF SEDIMENT-LADEN ICEBERG OBSERVATIONS—DEEP FREEZE 79. REFER TO FIGURE 2 FOR LOCATIONS

<i>Sighting No.</i>	<i>Position</i>	<i>Description</i>
1	lat. 66° 40' S. long. 141° 50' E.	Tilted iceberg, sediment in shear zones, layers approximately 12 m thick
2	lat. 66° 41' S. long. 145° 12' E.	Overtaken iceberg and several pieces, at least 15 m thick basal debris zone
3	lat. 67° 36' S. long. 148° 22' E.	Overtaken iceberg, basal debris zone 3 m thick
4	lat. 66° 01' S. long. 147° 04' E.	Tabular iceberg, sediment in shear zones, debris layer 2 m thick
5	lat. 65° 00' S. long. 165° 54' E.	Overtaken iceberg, 5–15 cm thick sediment layers in shear zones
6	lat. 77° 04' S. long. 166° 54' E.	Pack ice with surface debris, numerous sightings
7	South-western Ross Sea, near Ferrar Glacier	Icebergs beset in pack ice, basal debris zones and sediment in shear zones

Our first sighting was of a large tilted iceberg with a debris layer approximately 8 m thick (sighting 1; Figs 2 and 3). The debris zone consisted of alternating sub-parallel layers of dirty and clean ice. Individual layers averaged a few tens of centimeters in thickness and could be traced for several meters laterally.

One sample of approximately 5 cm³ of debris-rich ice was recovered by lowering a snapper grab from the helicopter. When melted, the ice liberated 0.2 g of poorly sorted, clay- to granule-size debris. Several large clasts, including a large boulder approximately 1 m in diameter, were observed lying on the surface of the iceberg.

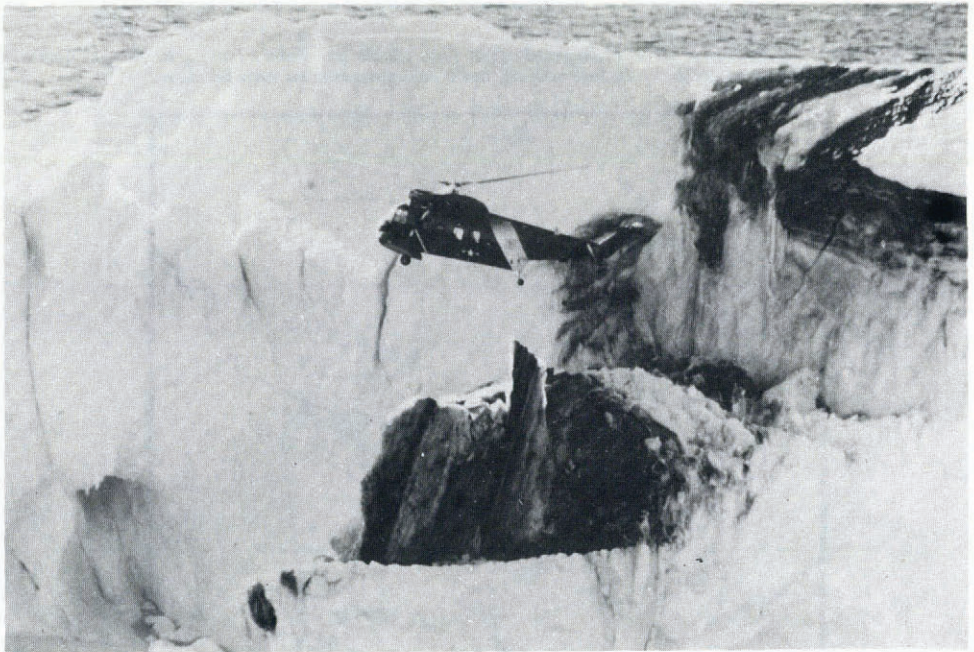


Fig. 3. A large tilted iceberg with debris zone approximately 8 m thick at an angle to glacier foliation; station 1 of Figure 2.

Shortly after making our first sighting, we discovered a number of debris-laden bergy bits near the calving margin of Mertz Glacier (sighting 2; Fig. 2). An overturned iceberg was discovered nearby which contained a debris-laden zone at least 15 m thick consisting of highly crystalline blue ice with distinct, sub-parallel layers of debris (Fig. 4). Dirty ice was in sharp contact with cleaner ice containing thin dirty layers. A small ice sample (approximately 10 cm³) collected from the debris-rich zone liberated approximately 0.5 g of sediment when melted. A grain-size analysis and microscopic analysis of this sample showed it to be unsorted and to consist of clay-to-granule size rock debris (Fig. 5). Only one large (approximately 25 cm) clast was observed on the surface of the ice.



Fig. 4. Overturned iceberg with thick (at least 15 m) debris zone in well-crystallized foliated ice. Sediment layers are sub-parallel to glacier foliation. Clean ice on the lower left corner of the iceberg is rime ice that was plastered on the surface of the iceberg. Station 2 of Figure 2.

Our third observation of debris-laden ice was within a few hundred meters of the sheer calving wall of Ninnis Glacier (sighting 3; Fig. 2). We examined this iceberg using the ship's Zodiac. Ice foliation was well developed (Fig. 6). A 3 m thick debris-rich zone was present above the water line and extended for several meters below the surface. The zone consisted of alternating sub-parallel layers of debris-laden ice and highly crystalline blue ice containing air bubbles and tubular air cavities (Fig. 7). Individual layers were a few centimeters thick. A sharp boundary separated the debris-rich zone from highly crystalline, sediment-free ice approximately 3 m thick (Fig. 6). Striated, prolate pebbles and cobbles, all consisting of slate, were scattered about on the surface and could be seen at depth within the ice.

Several sediment samples were taken from the debris zone and analysed for grain-size distribution and mineralogy. Samples from both individual debris layers and from composite layers were analysed. The average total sediment content of these samples was 6.4% by weight (range 4.7–7.8%). Textural analyses of these samples generated bimodal size-distribution curves with modes in the medium sand (0.5ϕ to 2.5ϕ) and coarse silt (5.5ϕ to

7.5 ϕ) ranges (Fig. 5). Microscopic examination revealed that quartz was the dominant mineral present in all size fractions. Sand-sized material contained a large percentage of spherical, frosted quartz grains, whereas the silt-sized fraction consisted of angular quartz fragments.

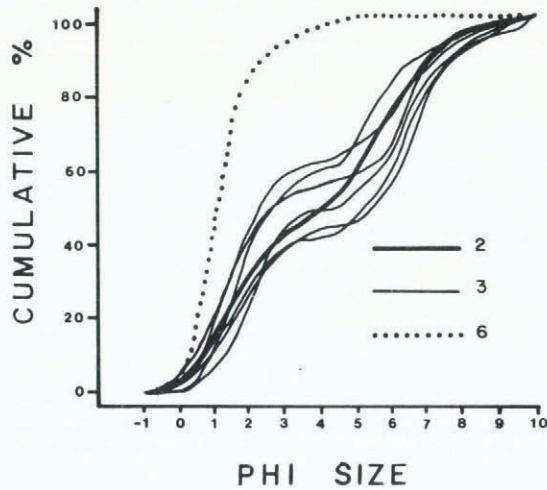


Fig. 5. Cumulative curves for sediment samples collected from icebergs at locations 2, 3, and 6.

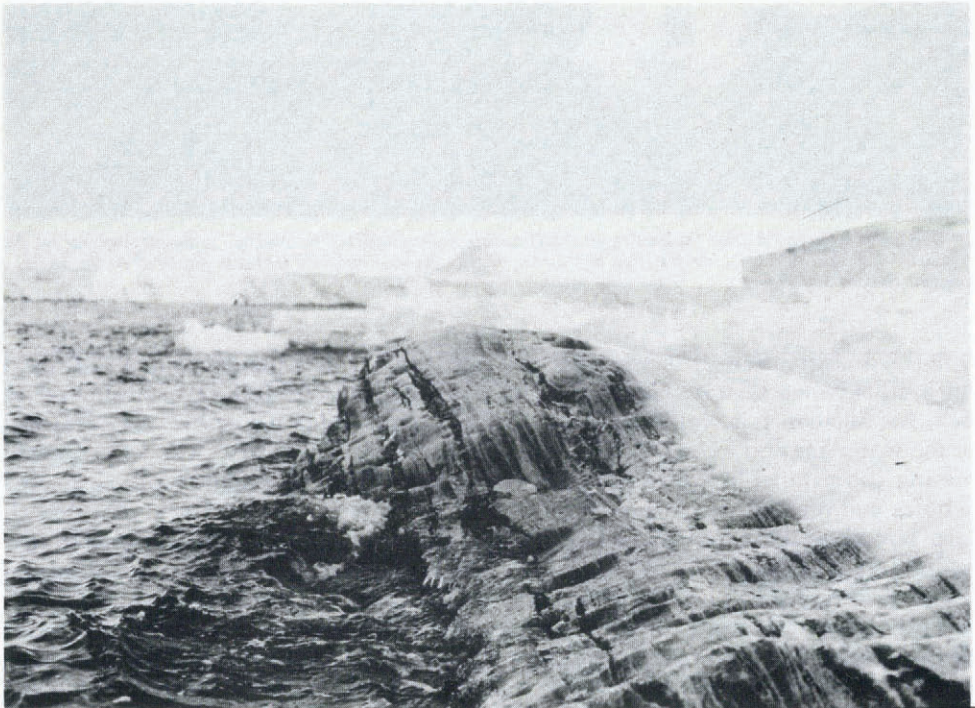


Fig. 6. Overturned iceberg with strongly foliated debris zone in sharp contact with clean ice. The sculptured surface reflects the highly crystalline state of the ice. The sheer calving wall of Ninnis Glacier is in the background; station 3 of Figure 2.



Fig. 7. A piece of highly crystalline, pure glacier ice with sediment bands, collected from the overturned iceberg shown in Figure 6.

Our last sightings in the George V Coast region was of a large tabular iceberg with a single 2 m thick debris layer oriented almost perpendicular to the ice layering (sighting 4; Fig. 2). Time did not permit a close analysis of this iceberg.

En route from the George V Coast to McMurdo Station, very poor visibility limited our iceberg observations. One sediment-laden iceberg was sighted at lat. $65^{\circ}00' S.$, long. $165^{\circ}54' E.$, our most northern observation of sediment-laden ice (sighting 5; Fig. 2). This iceberg appeared to be floating on its side and several thin (a few tens of centimeters thick) sediment layers could be seen just above the water line.

In the Ross Sea (sighting 6; Fig. 2), we encountered a number of pieces of loose pack whose surfaces were strewn with debris (Fig. 8). A sample collected from the surface of one of these pieces of ice consisted entirely of volcanic material ranging in size from boulders to coarse silt (Fig. 5). Very little or no fine silt- or clay-sized material was present.

During a reconnaissance flight along the coast near the Ferrar Glacier tongue in South Victoria Land, we discovered three sediment-laden icebergs beset in the heavy pack. Two of these icebergs had been eroded so badly that it was impossible to discern how the sediment was situated in the ice. A third iceberg displayed what appeared to be debris entrained along shear zones (Fig. 9). The iceberg appeared to be resting on its side so that the debris-rich zones shown in Figure 9 are oriented at approximately 30° to the ice layering.



Fig. 8. A small piece of pack ice approximately 4 m long with debris; station 6 of Figure 2.

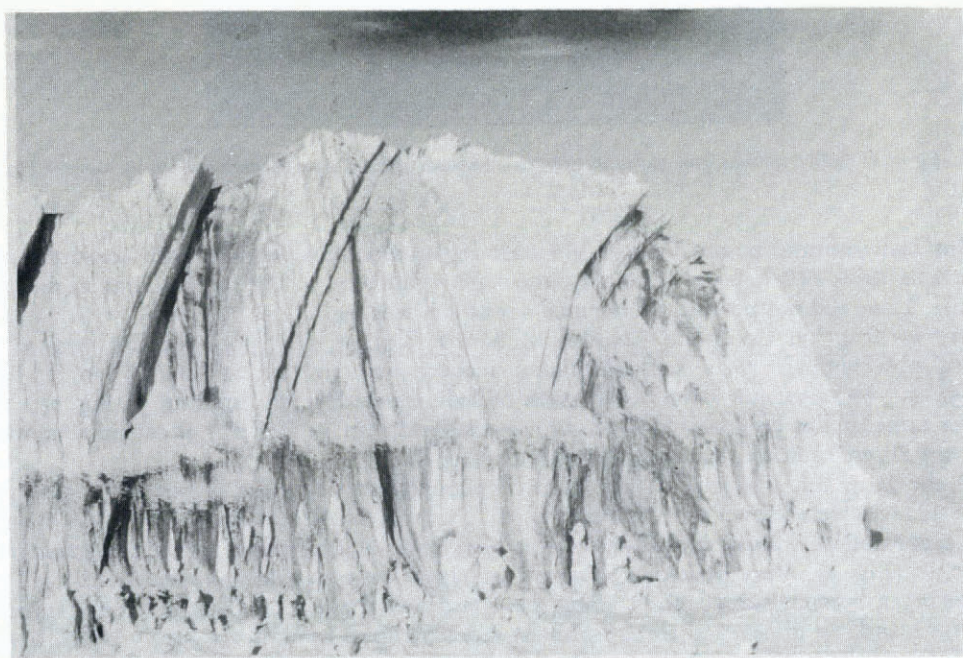


Fig. 9. A large tilted iceberg with sediment concentrated along shear zones oriented at approximately 30° to glacier foliation (approximately vertical in this photograph). Individual sediment zones are a few tens of centimeters thick. Station 7 of Figure 2.

DISCUSSION

The debris-laden icebergs observed during Deep Freeze 79 appear to represent at least three different modes of sediment transport. The second and third sightings were of what appeared to be the base of overturned icebergs and were made within a few hundred meters of the Mertz and Ninnis ice tongues (Figs 4 and 6). These icebergs possessed thick (in excess of 15 m in one case) debris-rich zones in which distinct sediment bands were interlayered with highly crystalline blue ice containing bubbles and tubular air cavities (Fig. 7). These zones occurred sub-parallel to glacier foliation. The process responsible for the incorporation of this debris is most reasonably that of pressure-melting-regelation, as these zones bear many of those characteristics described by Boulton (1970) in certain Svalbard glaciers. If formed in this manner, then the efficiency of this process at transporting debris to higher levels (over 15 m) may have previously been underestimated (Boulton, 1975).

During the Australasian Expedition of 1911-14, basal debris zones were described and photographed (Stillwell, 1918, pl. XIV, fig. 2, pl. XXXI, fig. 1) at Cape Dennison, just a few kilometers from where our second and third sightings were made.

The bimodal size distribution, high quartz content, and single pebble lithology of samples taken from one of these icebergs (sighting 3) are in contrast with common tills, which are generally unsorted and consist of diverse mineralogies. The size ranges observed are approximately the same as those produced by mechanical abrasion in the laboratory by Rogers and others (1963). Bimodality in these samples thus attests to the effectiveness of comminution through glacial abrasion.

The actual amount of debris melted from ice samples was smaller than expected, given the dirty surface appearance (range 4.7-7.8%). These concentrations are, however, greater than those reported by Goldthwait (1971) for basal debris zones in Greenland glaciers.

A second group of observations included debris-rich layers, ranging in thickness from a few tens of centimeters to a few meters and cutting through the ice at high angles (Figs 3 and 9). These layers were sharply bounded on either side by soft firn.

Conceivably, these debris layers could have been formed as glaciers flowed past submerged bedrock knolls, nunataks, or coastal outcrops. We did conduct helicopter flights over the vicinity of these sightings, but did not see any similar debris zones on the surface of the ice. We were impressed with the similarity of these debris layers to published descriptions and photographs of dirty shear planes (i.e. Goldthwait, 1951; Souchez, 1967). In fact, one of these icebergs (sighting 7) was within a few kilometers of Ferrar Glacier, where Souchez (1967) studied the formation of shear moraines.

A third mechanism of sediment transport involves supraglacial debris apparently slumped on to the surface of floating ice. These observations (sighting 6) include small bits of sea ice laden with volcanic debris of all sizes. The source of these sediments was undoubtedly very near the positions at which they were observed.

The fact that ice-rafting in Antarctica involves more than one mechanism is, within itself, quite important. It is also important to note that most of the debris zones we observed were apparently composed of material that had been raised up into the ice from the glacier bed. The mechanisms involved in this type of debris entrainment are fairly well understood, but the relationships between debris entrainment and glacial regime are still a matter of contention (Nye, 1952; Weertman, 1961; Goldthwait, 1971; Boulton, 1975). We would caution against using ice-rafted debris as a sole indicator of paleoclimates until our understanding of these relationships is improved.

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